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High Laser Pulse Repetition Rate Ablation of the CIGS Thin-Film Solar Cells

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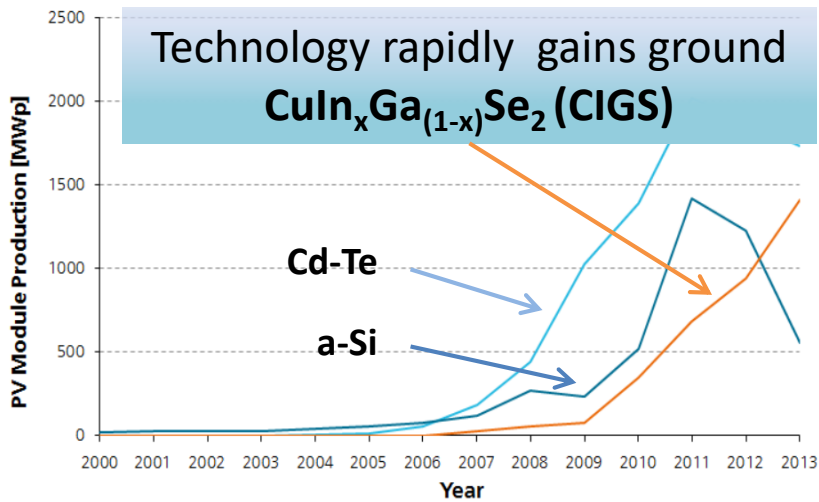
Motivation: Thin-film solar module industry

By the year 2050, 20% of needed energy will be harvested from sunlight

<http://ec.europa.eu>

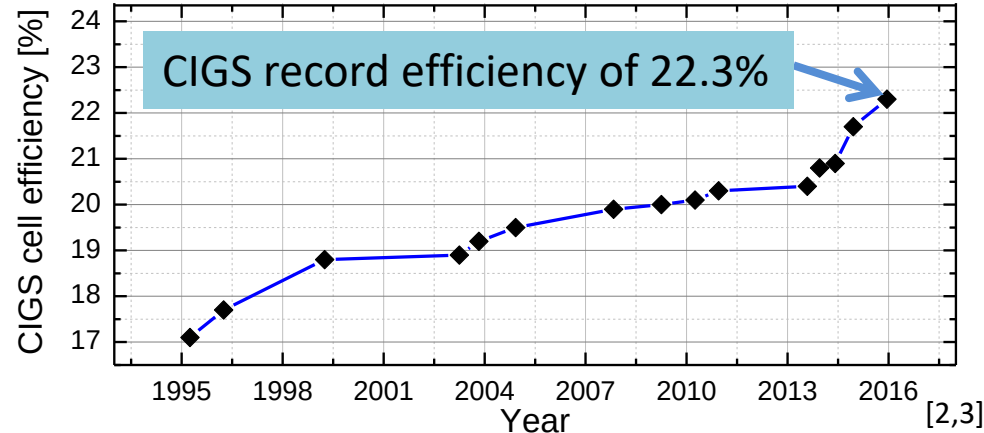
pros of thin-film solar cells:

- ➡ Saving of materials,
- ➡ EPBT smaller compared to Si PV,
- ➡ Weight of modules,
- ➡ Flexible substrates.



Annual global thin-film PV module production

[1]



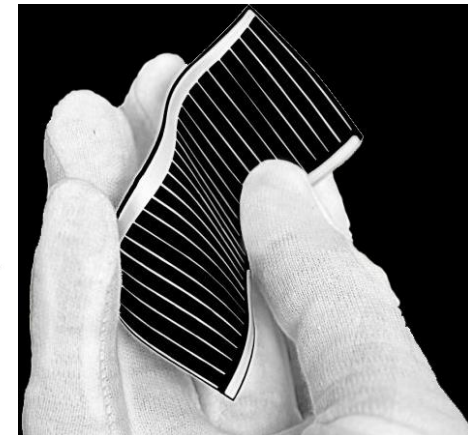
Development of laboratory solar cell efficiencies

[2] M.A. Green, et al., Solar cell efficiency tables (1995-2015)

[3] <http://www.solar-frontier.com/eng/news/2015/C051171.html>

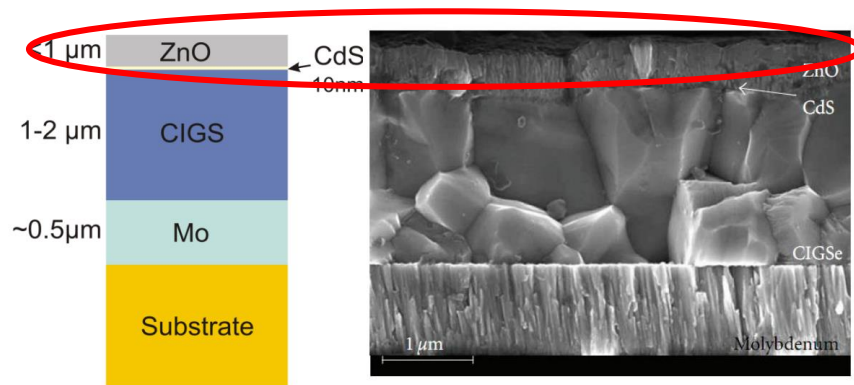


www.miasole.com



www.solarion.de

Motivation: From small to big



Typical structure of CIGS solar cell

To increase the amount of light reaching the absorber:

- Thin front-contact layers are deposited,
- It is done at the expense of reduced layer conductivity.

$$V_{oc} = \frac{E_g}{q} - 0.5 \quad \text{Generated voltage by a single cell is small (~0.5 - 1 V)}$$

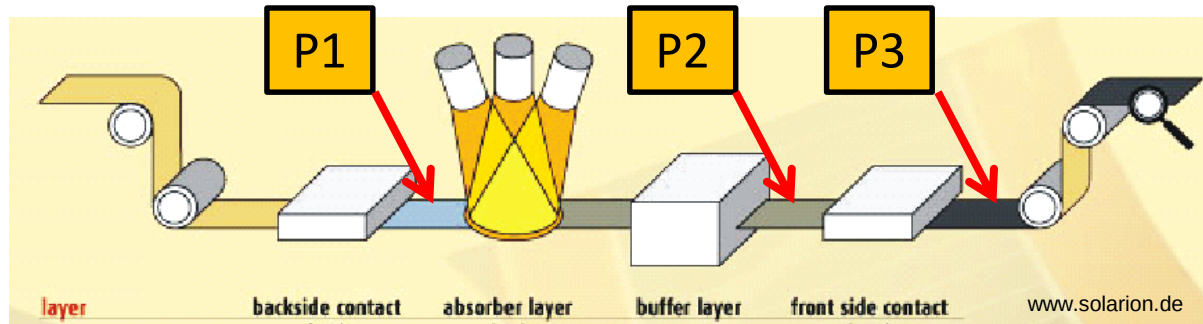
$$I_{ph} = J_{sc}A \quad \text{Generated photo-current } I_{ph} \text{ is linearly dependent on cell area } A.$$



300 A, but only 0.5 V!

High resistive losses incurred

Motivation: Thin-film CIGS production and patterning technology

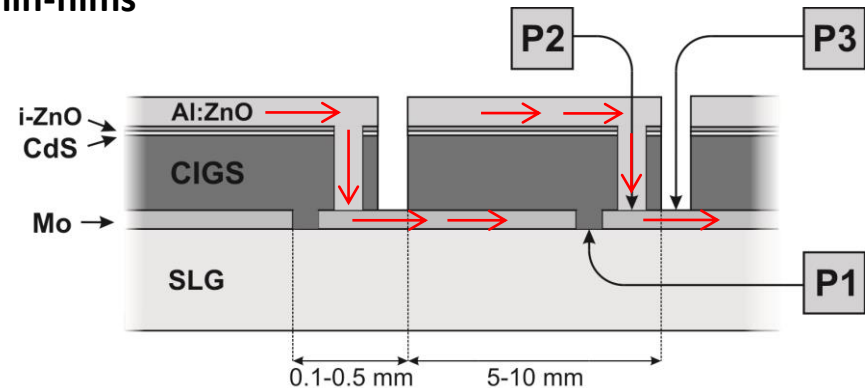


Patterning processes must be installed along the production line

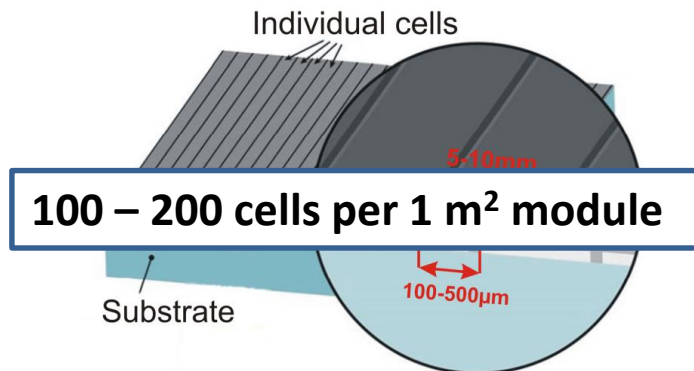
Typical production line of flexible CIGS thin-films

Scribing steps:

- **P1:** metallic back-contact formation,
- **P2:** absorber stripping,
- **P3:** cell isolation.



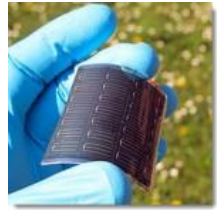
Cross-section scheme of a CIGS solar cell



$$V = n_{cells} * V_{OC} \quad I_{ph} = I_{ph,cell}$$

Motivation: Laser is a promising tool

best-solar-energy.com

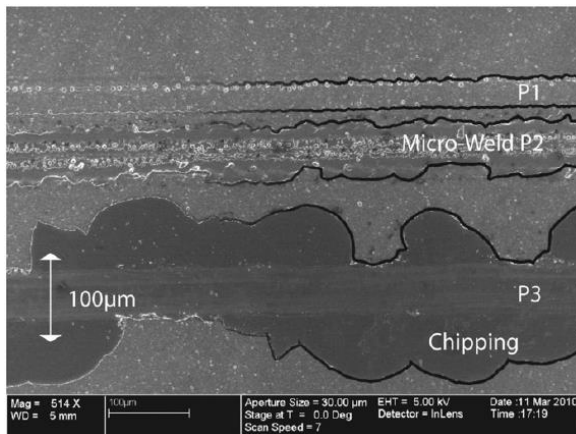


Achieved record efficiencies

	Cell		Module	
	eff, %	Area, cm ²	eff, %	Area, cm ²
CIGSe	22.3	0.5	15.7	9703

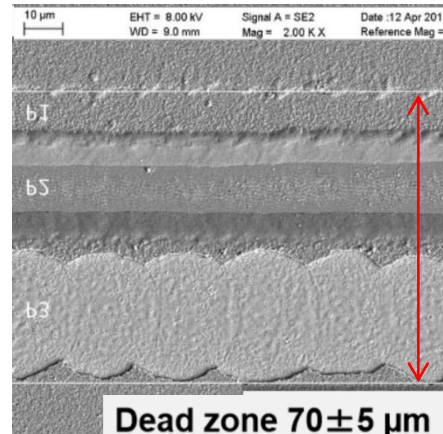
[5] M. Green, et al., Prog. Photovolt. Res. Appl., 24 (2015), 3-11.

Mechanical Scribing



[3] P.-O. Westin, et al., Prog. Photovolt.(2015).

All Laser



[4] S. Nishiwaki, et al., Sol. Energ. Mat. Sol.(2015).

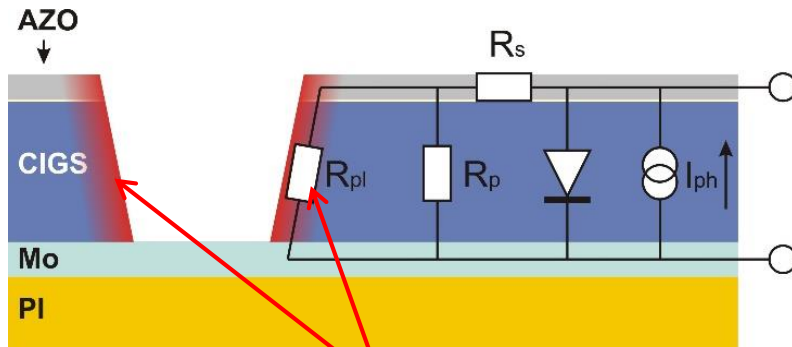
Much of this gap is due to:

- Non-uniformities encountered in the process of scaling up,
- Imperfections in serial interconnects.

Demands on laser technology:

Width 30-50 µm
Gap 15-50 µm
Speed >1-2 m/s
Layer selectivity
Reliability
Quality
No thermal damage

Motivation: P3 process is the most difficult!



Laser induced damage

Thermal damage to the absorber can cause:

- CIGS structural changes,
- Electro-conductive phase formation,
- Increase in cell parallel conduction.

$$efficiency = \frac{V_m \cdot I_m}{P_{IN}}$$

Low fluence to avoid laser damage!

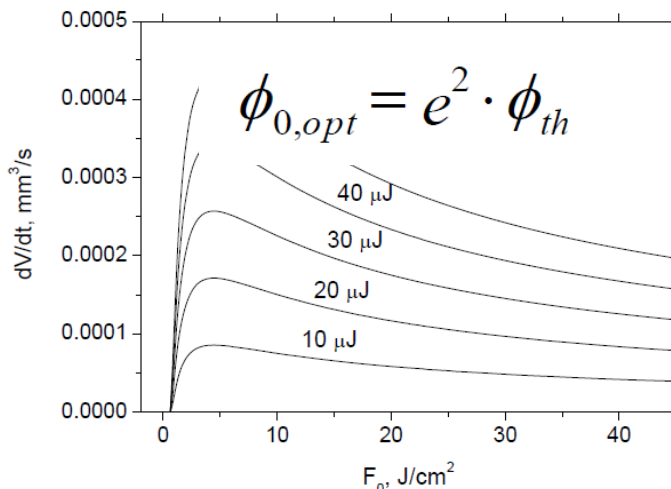
Common laser systems:

- 1064 nm
- ~100 kHz
- ~10 W
- Scribing speed ~0.2 m/s



Modern laser systems:

- 1064 nm, >1000 kHz, >50 W, >2 m/s



Material removal rate as a function of laser fluence

[6] G. Račiukaitis, et al., J. Laser Micro/Nanoen., 4 (2009),186 - 191.

The aim of the research

Investigate the P3 laser processing of the CIGS thin-film solar cells in case of the high-speed regime at high pulse repetition rates (1 MHz).

Experimental setup

Laser	Atlantic series (Ekspla)	
Pulse dur.	13 ps	
Rep. rate	Up to 1MHz	
Wavelength	1064 nm/ 532 nm	
Scanner	ScanLab	Next Scan Technology
Optics	80 mm	190 mm

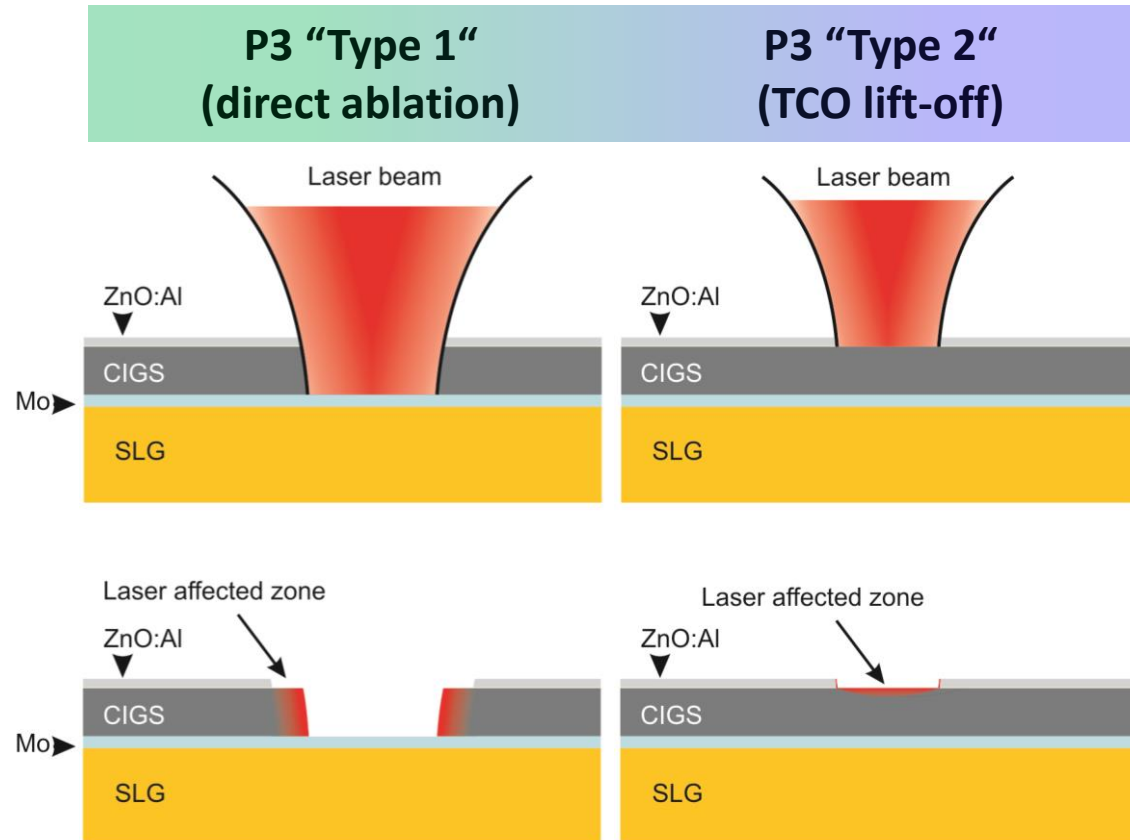


Samples

- **P3:** Complete structure solar cell:
(ZnO:Al/i-ZnO/CdS/CIGS/Mo/Glass).

Samples obtained from EMPA

Different P3 scribing approaches investigated

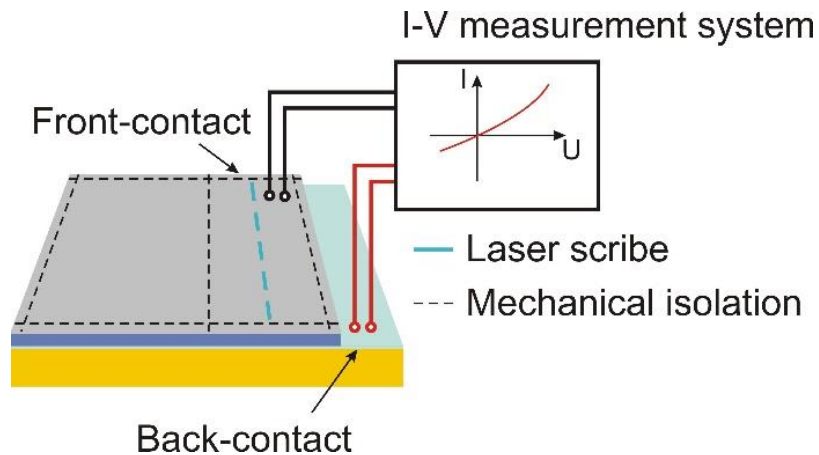


- Low energy pulses
- High pulse overlap

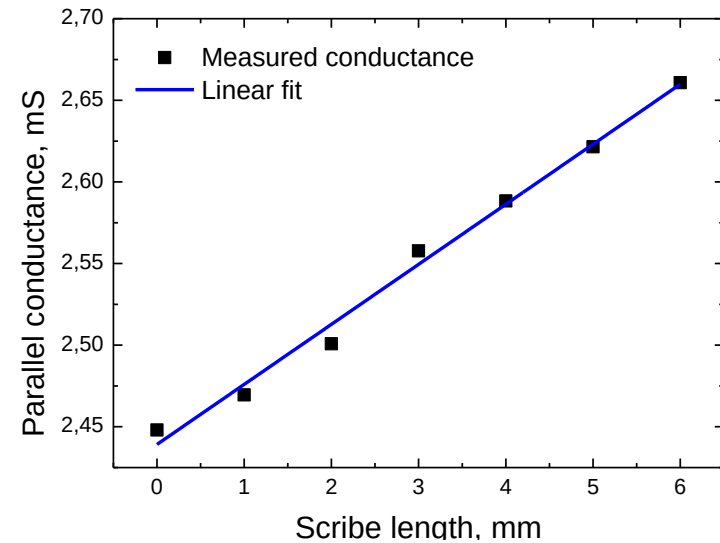
- Single shot process
- Low pulse overlap

Experimental setup: LLST measurements

Linear Laser Scribing Technique



LLST measurement scheme



Result of solar cell conductivity measurements

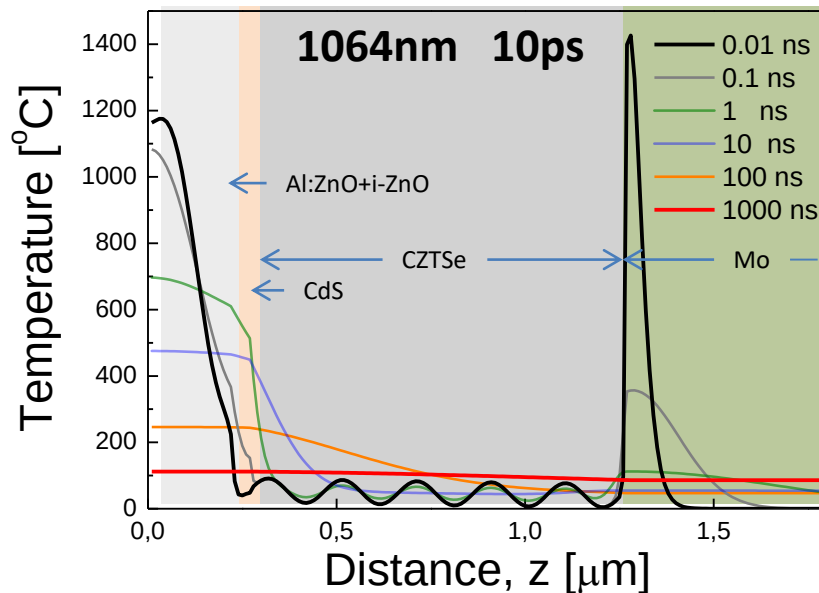
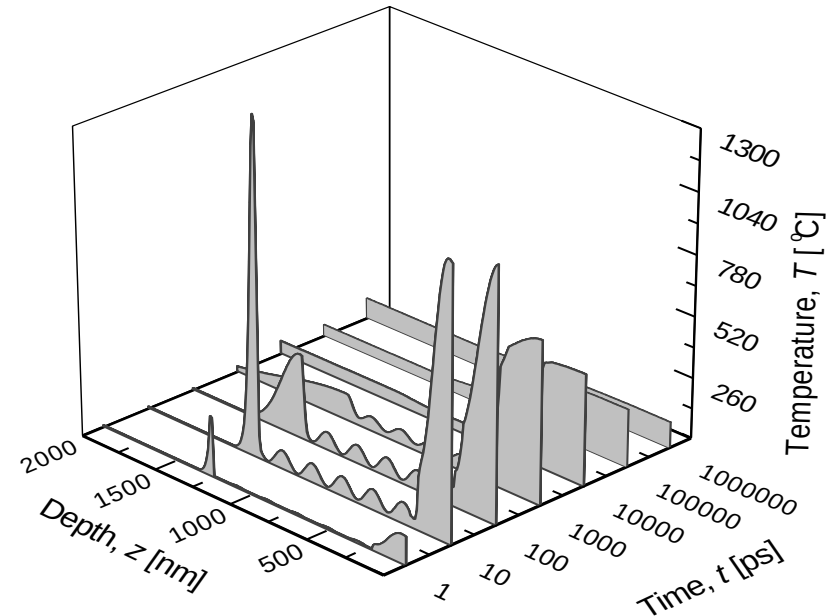
Linear fitting function

$$G_p^{SC} = \sigma_{SCM} \cdot l + G_{cell}$$

- Simple and fast technique,
- Small cell area consumption,
- Shows laser induced parallel conductivity.

[7] E. Markauskas, et al., Sol. Energy., 120 (2015), 35-43.

Simulations: Temporal temperature distribution in thin-film solar cell



Temperature distribution in CZTSe solar cell after 10 ps laser pulse irradiation

Heat transfer equation:

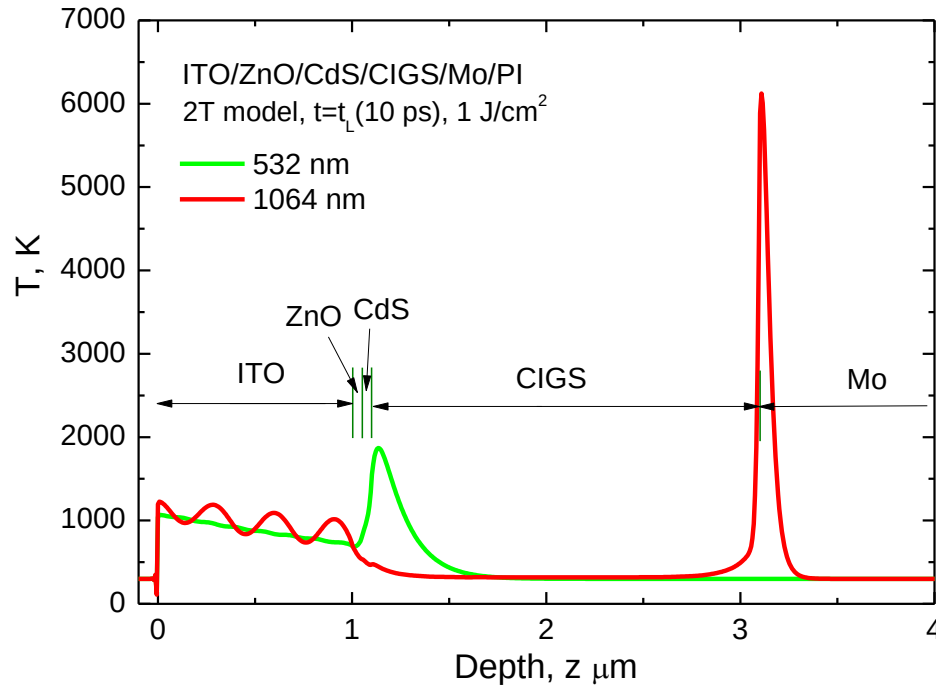
$$\frac{\partial T}{\partial t} = \alpha_{\text{diff}} \frac{\partial^2 T}{\partial z^2} + (1 - R_\lambda) \frac{\alpha}{\rho C_p} I(t) \exp(-\alpha z)$$

Reflectivity of layers:

$$R_\lambda = \left| \frac{\tilde{n} - 1}{\tilde{n} + 1} \right|^2 = \frac{(n-1)^2 + k_{\text{ext}}^2}{(n+1)^2 + k_{\text{ext}}^2}$$

[8] P. Gecys, et al., Sol. Energy., 102 (2014), 82-90.

Simulations: Temperature dependence on the laser wavelength

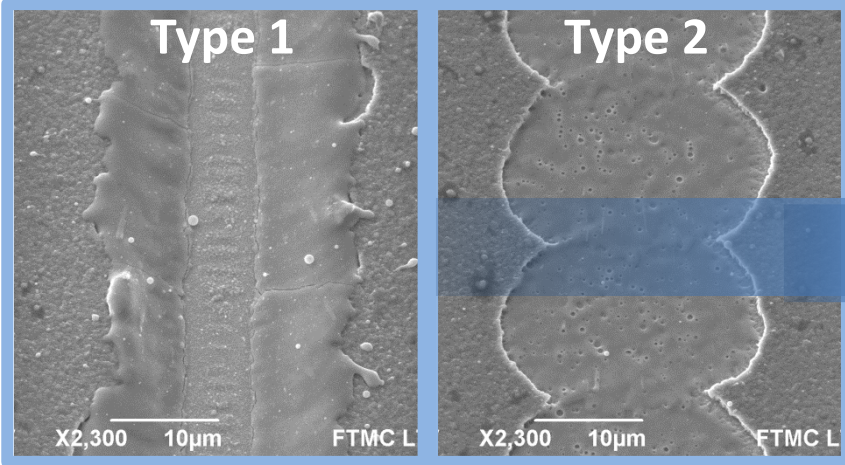


Temperature distribution in CIGS solar cell after 10 ps 532 and 1064 nm pulse irradiation.

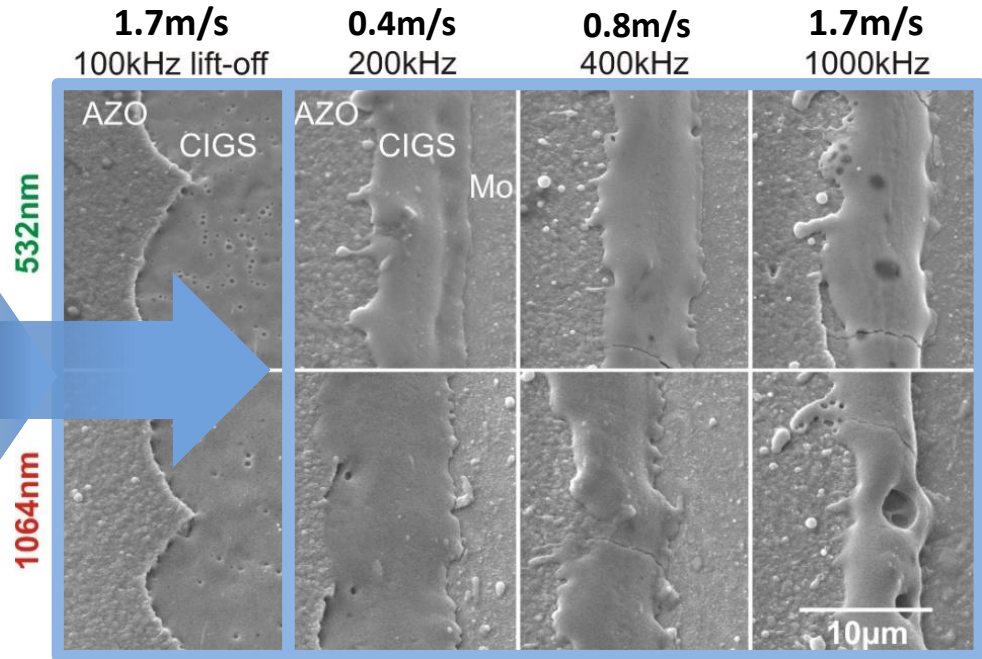
[9] G. Račiukaitis, et al., Appl. Phys. A, 112 (2013), 93-98.

Results: Laser P3 scribing

532 nm laser wavelength



Typical front contact lift-off and direct ablation channels in CIGS structure

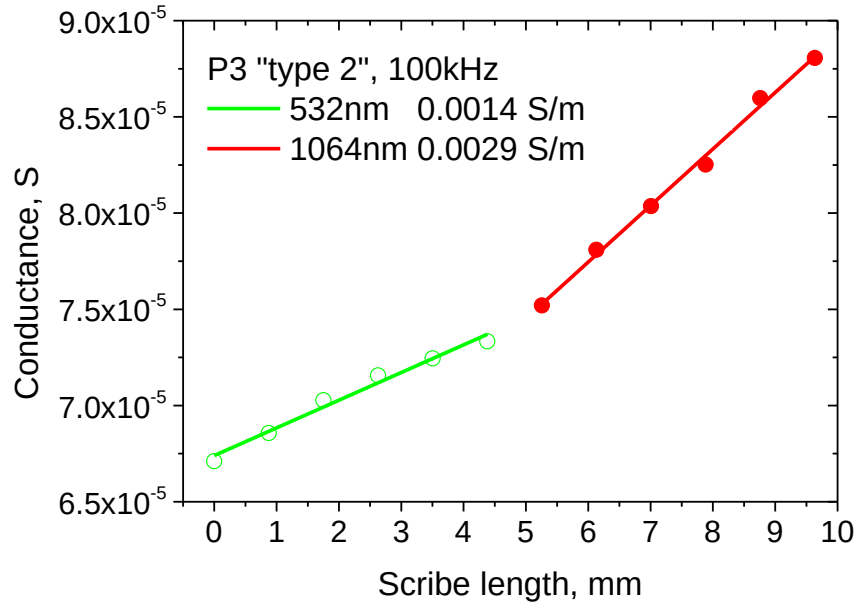


SEM images of P3 channel edges

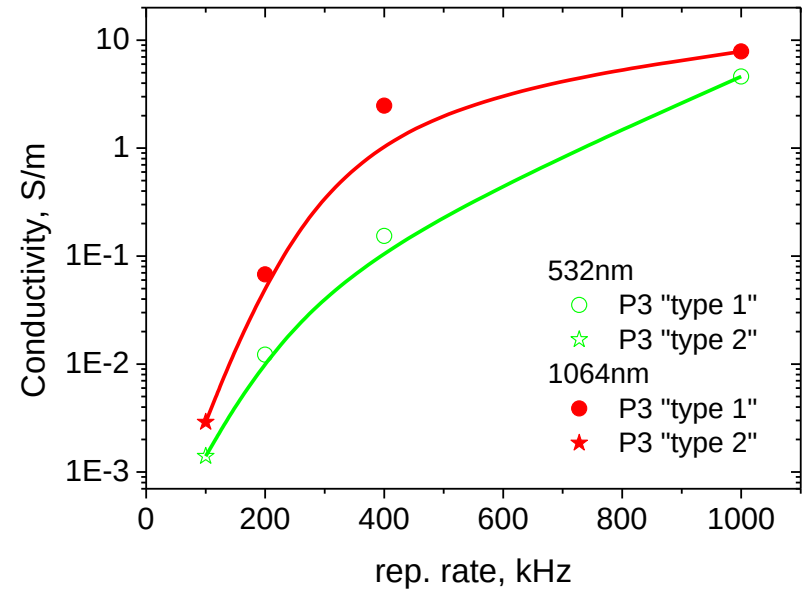
Laser processing parameters used in CIGS scribing

No.	P3 process	Rep. rate, kHz	Fluence, J/cm ²		Speed, m/s	Pulse overlap, %
			1064nm	532nm		
1	type 2	100	1.7	1.6	1.7	23
2	type 1	200	3.8	2.9	0.4	91
3	type 1	400			0.8	
4	type 1	1000			1.7	

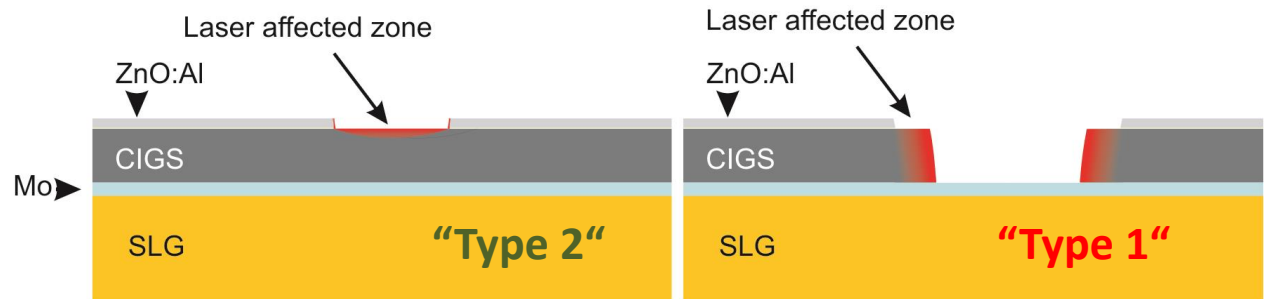
Results: LLST measurements of P3 laser scribes



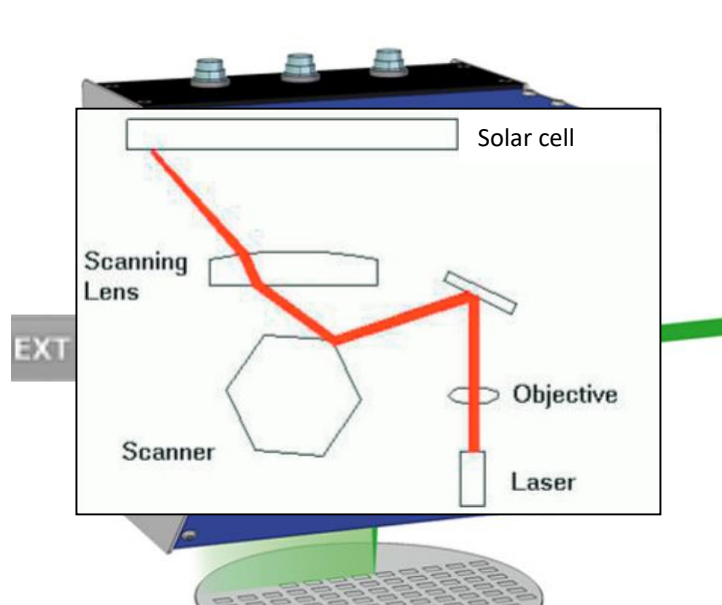
P3 "Type 2" scribe conductivity measurement at the same cell area for both laser wavelengths



Laser scribe conductivity vs. laser repetition rate



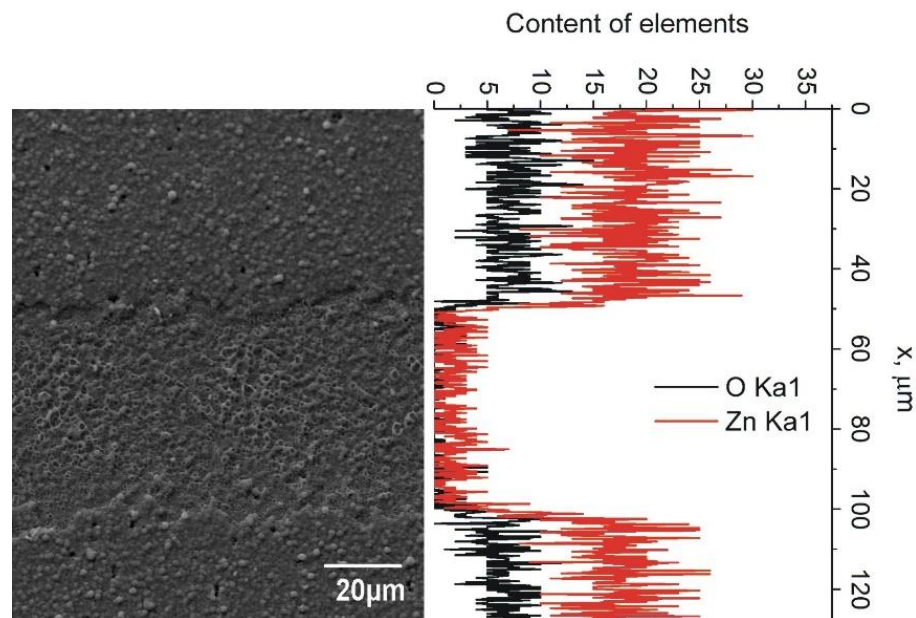
Results: Ultra-high speed scribing



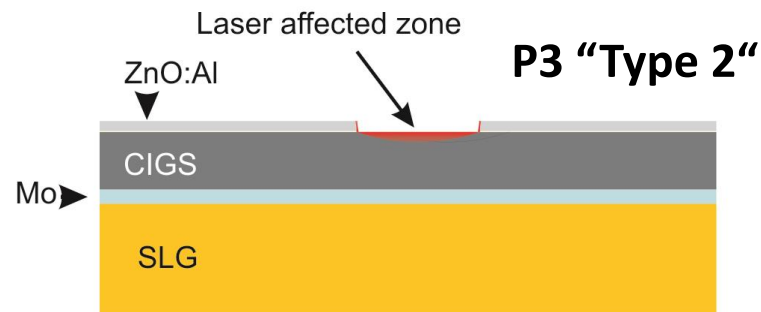
Next Scan Technology LSE170

[11] R. De Loor, Phys. Proc., 41 (2013), 544-551.

- Scanning speed: 50 m/s
- Laser repetition rate: 1 MHz
- Wavelength: 1064 nm
- Fluence: 2.6 J/cm²



- Fine scribe quality shown by SEM,
- EDS confirmed removal of ZnO layer.
- Low pulse overlap



Conclusions

Two P3 approaches were investigated in case of high pulse repetition rate scribing:

- Upscaling the P3 process is very challenging.
- Heat accumulation effects becomes highly dominant.
- Traditional “Type 1” process shows high scribe conductivity dependence on the laser repetition rate.
- Type 1: Highest conductivity reached 7.9 S/m at 1 MHz rep. rate and 1.7 m/s scribing speed. At these conditions 3-cell mini module suffered from severe efficiency losses.
- Type 2: No efficiency losses at scribing speed of 1.7 m/s. Extracted scribe conductivity was equal to 0.0014 S/m at 532 nm.
- Experiments showed that Type 2 process is a better solution for P3 patterning of CIGS thin-film solar cells.
- Scribing speed of 50 m/s was shown by exploiting polygon scanner combined with 1 MHz laser.

Thank You for Your attention

The research leading to these results was partially funded by the European Union FP7 Programme under grant agreement No 609355 (**apollo**).